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The phenomenon of energy concentration in combustion waves and its applications

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Abstract

The problem of energy concentration in combustion waves is considered. On the example of natural flames with an energy excess it is shown these flames can exist in various systems and different combustion regimes. The existence of some flames such as cellular and spin itself is due to an excess energy. The mechanisms of energy concentration are also varied. Besides the heat exchange processes such as conduction, convection, radiation the mass exchange processes, filtration, phase transformations and compressibility of gas may participate in the energy concentration. Although the phenomenon itself is known for a long time but its properties, characteristics and peculiarities are insufficiently studied. On the other hand, the given examples of flames with artificially created conditions for energy concentration demonstrate the wide applicability of this phenomenon.

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1. Introduction

Combustion processes are commonly controlled on a basis of chemical or physical parameters. In the former case, use is made of the reacting mixture parameters (mixture composition, parameters of chemical reaction, combustion rate, etc.). In the latter case, advantage is taken of the parameters that control thermal, aerodynamic and other physical characteristics of combustion. These conventional methods are well known and substantially limited. Therefore, of interest are the untraditional methods of control which involve such flame property as self-organization, in particular, the phenomenon of energy concentration in combustion waves known in the literature as the term of "excess enthalpy". The problem of combustion with excess enthalpy or energy (EE) has been considered in many papers including the reviews considering mainly the combustors [1,2]. However, according to a recent remark by Weinberg [3], the phenomenon of EE, is more frequent in nature than is has been accepted. It is necessary to further analyze combustion processes with EE to search for general regularities and develop the physics and chemical foundations for various applications.

The present paper analyzes some aspects of the problem of "excess energy flames" (EEF). In systems, which methods and elementary processes involved the EEF formation occurs? What are prospects of the use of EEF principles and properties in practice (burners, reactors, and technologies)?

The early conceptions of the phenomenon of energy concentration in flames are apparently pertained to the 30th year. Lewis and Von Elbe [4] analyzing the relationship of the chemical and thermal parts of energy in the general enthalpy of combustible mixture concluded that "excess enthalpy" occurs in the flame zone when the coefficient of thermal diffusivity of mixture, χ, exceeds the diffusion coefficient of a deficit component D. This conclusion has been drawn for flat laminar flames.

2. Excess energy flames

2.1. Cellular flames

It appeared that the phenomenon of excess energy could be observed in distorted flames. However, the mechanism of EE formation differs from that of flat flames [5,6]. This case is implemented in e.g. very lean hydrogen air flames. The Lewis number $Le = \chi/D < 1$ and in convex (towards fresh mixture) regions of flame front there are more favorable conditions for hydrogen ingress into the zone of chemical reaction as compared with the concave front regions. As a result at convex front the hydrogen concentration in the

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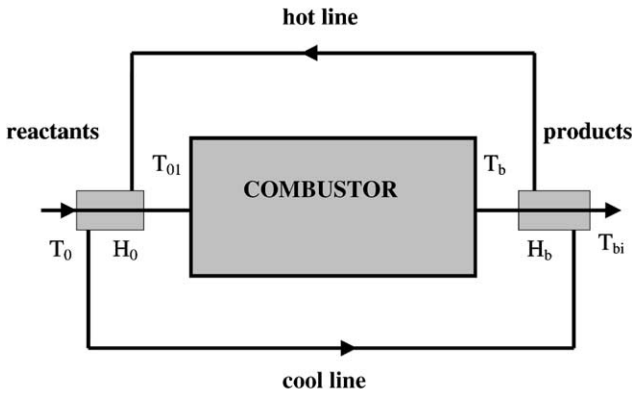

Fig. 1. A burner with external heat recuperation. H_0, H_b—heat exchangers.

flame zone is higher than its average level in the mixture and accordingly higher temperature. On this course lean hydrogen air flames propagate in the form of separate cells at average estimated temperature about 700 K. At such a low flame temperature, flat hydrogen flames can not propagate.

2.2. Regenerative burners

The method for using combustion products heat for increasing combustible mixture energy and improving the characteristics of combustors has long been known. In this case, one or two outer heat exchangers are usually applied (Fig. 1). As a result, the product temperature decreases. $T_{bi} < T_b$ and that of reactants increases $T_1 > T_0$. This leads to an increase in combustion rate and efficiency of a combustor. This simple idea is turned out highly effective and its practical use has many modifications [7,8].

Thus, in the 1980s, the method of reversing regenerator developed by the British Gas Company for heavy industry (smelting of scrap iron, glass, etc.) [9] has been widely used. Schematically, a smelting furnace with a system of reversing regenerator has two combustors that operate in turn (Fig. 2). First, combustor C_1 starts working. Combustion products pass through combustor C_2, heat exchanger H_2 (a bed of alumina shapes) and after cooling are exhausted. When heat exchanger H_2 is heated, gas flows change their directions into opposite one. Then combustor C_2 is started. Combustion products pass through combustor C_1, heat exchanger H_1 (similar to H_2) and after cooling, are exhausted. According to the data of British Gas, this system allows one to utilize 90% of the heat of exhausted gases and have a great saving in fuel.

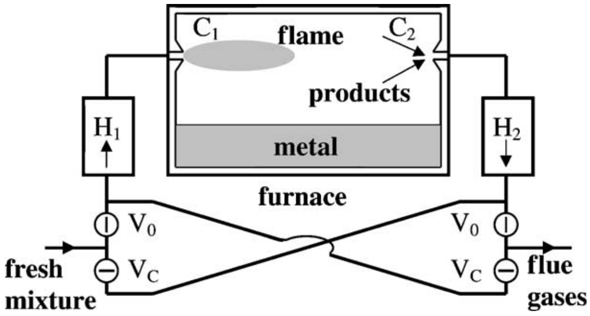

Fig. 2. Smelting furnace with external heat recuperation. C_1, C_2—burners; H_1, H_2—heat exchangers (bed of alumina shapes); V_O, V_C—valves in open and closed positions.

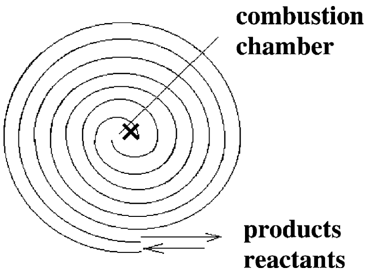

Fig. 3. Regenerative double spiral burner.

In a more compact form, the idea of heat recirculation with an outer heat exchanger is given in the system of "double spiral" or "Swiss roll" proposed by Lloyd and Weinberg [10]. In this case, heat exchangers at combustor exit and entrance are combined into a single exchanger (Fig. 3).

2.3. Tunneling burner

The principle of excess energy is also implemented in conditions of a tunneling burner [11] with two characteristic constructive elements. Firstly, the burner is of the form of a tunnel whose walls are lined with refractory material (ceramics) and, secondly, the scheme of combustion process is such that in the region of natural flame stabilization at torch root there is the reverse circulation of combustion products (Fig. 4). Owing to product recirculation, hot products are admixed into the jet of fresh mixture. Thus, there occurs stable ignition, local increase in burning velocity, and finally, the improvement of the blow-off characteristics of the burner. It has been observed that in a short combustor, cold gas passes from the environment to the zone of reverse circulation due to the suction that causes the combustion blow-off. This testifies to the significant role of hot combustion products. The function of the ceramic lining is to support high temperature of the mixture and products in the region of

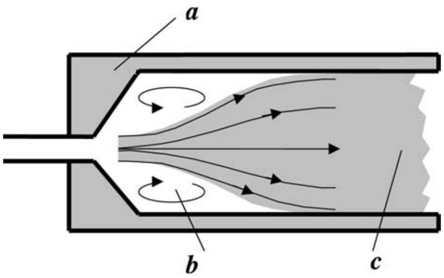

Fig. 4. Sketch of tunnel burner: (a) ceramics; (b) region of circulation of products; (c) combustion products.

reverse currents. The high temperature of the combustor walls is provided by all components of complex heat exchange: conduction, convection and radiation. Note that the high efficiency of a tunneling burner is related first of all to its high stabilization characteristics. Thus, the tunneling burner contains the elements of combination of the recuperation and combustion processes. This combination, however, is of a local character (the region of reverse currents) and has directly no effect on the main combustion zone. The inner recuperation is fully manifested upon combustion in a porous medium.

2.4. Stabilized combustion in a porous medium

Takeno and Sato [12] have theoretically considered the phenomenon of energy concentration upon combustion of gaseous mixture in a half-limited inert porous medium. Since they analyzed only stabilized flames (immovable relative to a porous medium), the equilibrium temperature T_{eq} was equal to the adiabatic temperature of usual (without porous medium) gas flames, T_{b}. It is shown that the zone of chemical reaction has the peak of nonequilibrium temperature that substantially exceeds the adiabatic flame temperature, T_{b} (Fig. 5). The temperature peak is determined by the internal heat recuperation in the flame zone. Some heat of combustion products is transferred by conduction through a solid carcass to the preheat zone. Because of conductive recuperation in the preheat zone the carcass temperature, Θ is higher than that of gas, T (Fig. 5). Therefore, before ignition, the combustible mixture is additionally heated which results in the formation of the peak of superadiabatic temperature. This result was a theoretical base for the possibility of combustion of low-calorie gaseous mixtures that are beyond flammability limits under usual conditions. The conclusions of [12] were confirmed by further experimental and theoretical works [13–15].

2.5. Travelling combustion waves in a porous medium

Quite a different situation arises with internal heat recuperation upon combustion wave propagation in the inert porous medium in low velocity regime (LVR) [16–18]. In this case, the equilibrium combustion temperature, T_{eq}, is not equal to the adiabatic temperature of usual flame, T_{b} (except the case $u = 0$). Upon steady-state wave propagation, the equation for equilibrium temperature is of the form [17] $T_{\mathrm{eq}} = T_0 + (Q/C_T)(v - u)/(v - (1 + \sigma)u)$, $\sigma = (1 - m)(C_\Theta \rho_\Theta / m C_T \rho_T)$, where T_{eq}, T_0 are the equilibrium and initial temperatures, u, v are the velocities of combustion wave and gas filtration, Q is the reaction heat release, C_T, C_Θ are the heat capacities of gas and solid phase, ρ_T, ρ_Θ are the densities of gas and solid phases, and m is the porosity.

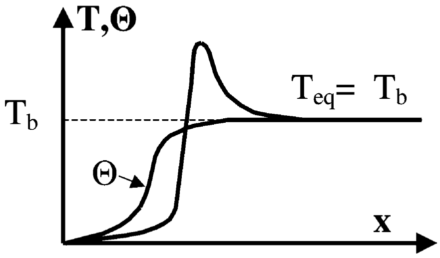

Fig. 5. Thermal structure of stabilized combustion wave of LVR. θ, T—temperature of solid and gas phases; T_{b}—temperature of laminar flame.

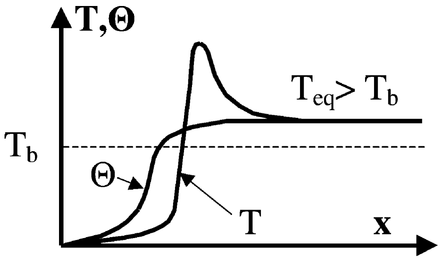

Fig. 6. Thermal structure of coflow combustion wave of LVR. θ, T—temperature of solid and gas phases; T_{b}—temperature of laminar flame.

As follows from the equation, at $u > 0$, the equilibrium temperature exceeds the adiabatic one $T_{\mathrm{eq}} > T_0 + (Q/CT)$ (Fig. 6). If we consider combustion process in the system of coordinates moving together with the zone of chemical reaction, it is seen that the hot porous medium moves from the region of combustion products to the region of fresh mixture passing through the zone of chemical reaction. The heat is effectively transferred with porous medium to the preheat zone by convection. Here it is transferred into the gas-phase increasing its temperature. It is important that the convective heat recuperation allows one to increase the equilibrium temperature, to raise a potential of utilized heat. Note that in the coflow travelling combustion wave the conductive recuperation leading to the superadiabatic nonequilibrium temperature in the zone of chemical reaction is preserved. However, there appears additionally the superadiabatic equilibrium temperature owing to convective heat recuperation. In other words, the coflow travelling waves display a novel characteristic, i.e. superadiabatic equilibrium temperature absent in stabilized flames.

2.6. Reverse-process with gas-phase reaction

The phenomenon of superadiabatic equilibrium temperature described in the previous section has been first observed in porous systems in the waves of chemical transformation with heterogeneous reaction [19–21]. Later, this property of EEF has been used in a practical system “reverse-process” [22] schematically shown in Fig. 7. The reactor is symmetric about exit and entrance. At its center, there is a porous layer of a catalyst (a). From both sides of the catalyst, there are layers of inert porous medium playing the role of heat

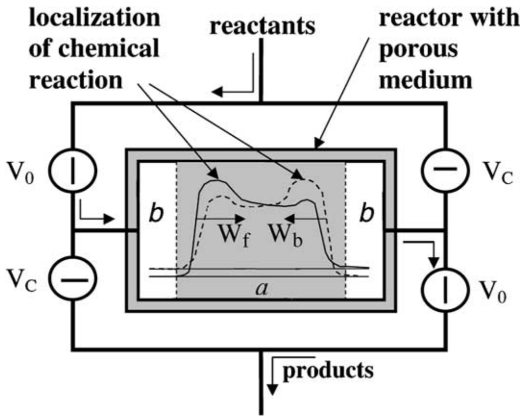

Fig. 7. Scheme of the reverse-process: (a) porous catalyst layer; (b) layer of inert porous medium; W_f, W_b—waves moving in forward and backward directions; V_O, V_C—valves in open and closed positions.

regenerators (b). The scheme of gas flow control allows one to change periodically the direction of the flow in the reactor by switching valves (V). After catalyst ignition, the chemical transformation wave in the form of a Π-shaped pulse travels towards the gas flow (W_f). In this case, the chemical reaction is localized not on the leading wave front (heating front), but on the back front (cooling front). When half the working period of the reactor, t_h, is over, the direction of the reaction mixture flow changes and the wave moves back (W_b). The chemical reaction is also localized at the back front of the Π-shaped wave.

The studies of the combustion wave in inert porous media performed early in the 1980s show the possibility of implementing a reverse-process with gas reaction in the low velocity regime (LVR) [16,17]. Indeed, equations of heat balance describing heat structures of the gas-phase and catalytic travelling waves in the LVR are the same for fine-disperse porous media. Thus, the EE phenomenon and superadiabatic equilibrium temperature described in the previous section are of universal character, i.e. are independent of the type of chemical reaction. The reverse-process with gas-phase reaction has been implemented in the reactor made of a quartz tube 500 mm long and 40 mm in diameter filled with a fraction of carborundum of 2–2.5 mm in LVR [23]. It was shown that in the reverse system with strong heat losses the nonflammable propane–air mixture containing 1.7% of C_3H_8 can burn steadily. At the same time, some problems appeared with implementation of the reverse-process because of the possibility of the Π-shaped wave breakdown into two separate waves, the formation of waves asymmetric about reactor center, the influence of gravitation convection, spatial instability of combustion front and retention of "hot area" in restricted the space of reactor. New data have recently appeared on the possibility of burning out gaseous mixtures by the reverse-process with gas-phase reaction with extremely low equivalence ratio of 0.026 and producing low NO_x and CO emissions of the order of ppm [24].

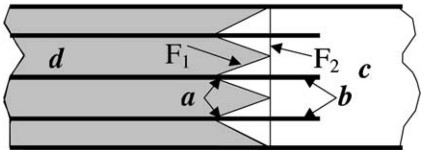

Fig. 8. Scheme for elucidation of influence of heat-conducting elements (HCE) on combustion rate of energetic material. F_1, F_2—area of combustion surface of a sample with and without HCE accordingly: (a) hot-spots; (b) HCE; (c) combustion products; (d) initial energetic material.

2.7. *Combustion with heat-conducting elements*

In the sixties, the attention of researchers has been focused on the fast combustion of samples of solid energetic materials (powder) after introduction of some metals in the form of thin wires called the "heat-conducting elements" (HCE) into the samples [25,26]. HCE causing the greatest acceleration of combustion have high temperature conductivity and their mass fraction in the body of energetic material is optimal. Studies show that the mechanism of combustion acceleration is related to an increase in the area of burning surface (F_1) with respect to the combustion area without HCE (F_2) (Fig. 8). Combustion area increases due to the formation of the leading hot-spots (a) located near HCE (b). The hot-spots result from effective conductive heat transfer through HCE from the zone of combustion products (c) to the zone of initial energetic material (d). Thus, HCE accelerate the heating, ignition and burning of the local volumes of energetic materials located near them. In this case, the main body of fuel is not heated by HCE. It is interesting that the internal heat recuperation is determined by the properties of metallic wires energetic material. It is of a local character and results in an increase in the general mass combustion rate.

2.8. *Spiral combustion*

The unusual gasless combustion with excess of energy has been observed in [27]. A sample in the form of a pellet made of iron-zirconium thermit diluted by reaction products, was ignited at the center of the pellet. A tangential spreading of the local hot-spot of chemical reaction has been observed instead of the usual centrally symmetric radial combustion wave propagation (Fig. 9). The hot-spot moves by spiral with increasing diameter of the trajectory. As the spiral diameter increased, the radial hot-spot velocity decreased. When a certain diameter of the burnt region (c) was reached in the zone of fresh thermit mixture (a), the second, third, etc. hot-spots appeared. The direction of hot-spot movement became arbitrary, i.e. it could be coflow and counterflow. Further, this nonsteady-state spin regime was called the spiral combustion regime and studied theoretically [28].

The mechanism of spiral combustion is presumably related to the phenomenon of a quenching distance. In our

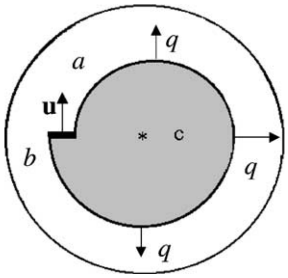

Fig. 9. Spiral propagation of combustion spot under central ignition of thermit sample: (a) initial substance; (b) combustion spot; (c) solid phase combustion products.

case, this means that the radial propagation of a circular combustion front is impossible in the pellet of thickness h that is smaller than some critical thickness h_c. The spiral combustion regime occurs just in this case, i.e. at $h < h_c$. The spiral propagation happens because during one rotation of the hot-spot (b), the initial substance (a) adjoining hot combustion products (c) is conductively heated by combustion products. In the thermit, the excess of energy is formed which is sufficient for the tangential hot-spot propagation. It is interesting that in this case, heat recuperation occurs without relative movement of reactants and products as in the case of "Swiss roll" (Fig. 3), but in the passive phase of the expectation of the "arrival" of hot-spot moving along the boundary of their contact. The existence of some other regimes of spiral combustion is also assigned to the phenomenon of energy concentration in the combustion wave [29].

2.9. Combustion with longitudinal self-oscillation

A rather interesting form of internal heat recuperation occurs upon combustion of gasless compositions with longitudinal self-oscillation of velocity [30]. At some values of the parameters, the steady-state combustion wave can lose its stability and pass to the longitudinal oscillation regime of propagation. In this case, the velocity and structural characteristics of flat combustion wave fluctuate. A stage of slow burning (depression) gradually passes into the stage of fast combustion. The latter converts into the stage of slow combustion and the process repeats.

Physically, the phenomenon of periodic propagation is determined by the "pumping" of initial substance by thermal energy supplied by hot combustion products beyond the stability limit of the steady-state propagation regime. This "pumping" occurring in the depression phase, i.e. at low wave velocity, leads to the fact that in the next stage of fast combustion, the maximum temperature exceeds 1.5–1.8 times the adiabatic one. As the overheated substance burns out, the combustion rate decreases with combustion temperature and the depression phase comes. Then, the process occurs again.

2.10. The sonic velocity regime (SVR)

The energy concentration in the combustion wave may be also due to compressibility of a gas. It is observed, in particular, at combustion of premixed gas in the systems with high hydraulic resistance, e.g. in inert porous media in the "sonic velocity regime" (SVR, flame velocity is an order of 10^2 m/s) [18]. In this case, the compression wave with increased state parameters is formed due to hydraulic resistance of expanding combustion products. As a result more favorable conditions for chemical reaction proceeding appear than in the initial mixture. The chemical reaction rate, burning velocity of the flame and combustion wave velocity are increased. Notice that a compression wave is formed and is supported by the combustion process itself and the cause of high speed combustion is the blockage of space. The effect is formally described by the coefficient of medium resistance, blockage ratio (in the case of periodical obstacles) or other parameters that characterized the friction of moving gas. The characteristic features of the combustion wave are baric wave with smooth pressure increase in the front, lower (comparing to detonation wave) level of maximal pressure and not uniform time–space distribution of heat release. The wave is steady; its velocity depends on structural parameters of porous medium and thermophysical properties of the combustible gas [31].

It is interesting to note that combustion waves in such processes as gas combustion at constant volume, deflagration-detonation transition, normal detonation (detonation of Zel'dovich–Neiman–Dering), in which concentration of energy proceeds due to compressibility of gas may be classified as EEF.

3. Discussion

The above examples of flames with energy excess show that energy concentration in combustion waves is a widespread phenomenon of combustion processes. It is likely to occur in all systems in which combustion is possible: homogeneous and heterogeneous, with and without gas, multiphase, disperse and other ones capable of combustion.

Combustion regimes, flames and combustion processes in which excess of energy is implemented are various. These are laminar and turbulent flames, stabilized combustion, travelling waves and diffusion flames [32]. It is interesting that the EE phenomenon causes the appearance of "exotic" flames such as cellular flames, spin and oscillating waves. Upon filtration combustion, owing to EE, the flames display unique properties such as nonequilibrium and equilibrium superadiabatic temperatures, the possibility to propagate flames in the channels with characteristic sizes lower than critical ones and others.

The mechanisms of excess of energy formation are also quite varied. First of all, of notice are two recuperation forms (internal and external) which create the EE effect. In internal recuperation, this process becomes the inherent property of the flame. From practical viewpoint this type of recuperation seems as more effective. In both of the cases, of importance are all components of complex heat exchange, namely, conduction, convection and radiation. The energy concentration involves not only heat exchange but also mass exchange processes, e.g. preferential diffusion (the effects of Lewis number). In this connection, it is of interest the specific mechanisms of returning part of heat release back to fresh mixture from the combustion products under flame stabilization of tunnel burner. In one of these cases this is reached by mixing of products with fresh mixture in the region of gas circulation. In the second case, by heating of ceramic coating at torch root mainly by radiation of both the torch and red-hot back part of the burner. In both cases heat recirculation favors stabilization of ignition and gas combustion. However, the concentration of energy occurs only in the second case. Favorable effect in the first case is due to increasing of local stationary value of temperature of reacting mixture under its simultaneous dilution with combustion products.

Besides the mentioned heat and mass exchange processes other processes may take part in energy concentration. They are gas compressibility (Mach number effects), mass forces (Rayleigh number effects), phase transitions, filtration of gas and liquid. The EE effects can, therefore be manifested in a change in temperature, mixture composition, density or pressure changes in both thermal and chemical parts of enthalpy.

On the other hand, an increase in the reactivity of mixture due to energy concentration can occur both throughout the flame front and locally, in separate hot-spots, cells, etc. Thus, an increase in temperature and, as a result, in combustion rate of energetic material at the leading points near the heat-conducting elements leads, nevertheless, to a global increase in the combustion rate of the entire energetic material. The most striking the EE properties appear near critical conditions at flammability limits, stabilization boundaries, etc. Another important aspect of EE manifestation is that additional heat from combustion products can be used not only in the heating of reaction mixture but in other processes such as evaporation, gasification and formation of combustible mixture above the surface of liquid fuel [32]. It is important to note that for maximal concentration of energy it is necessary the optimal conditions. Searching of these conditions is a separate problem. Application effectiveness of EEF depends on the solution of this problem.

Although the concept of “excess enthalpy” in flames is often used in the scientific literature and its physical meaning is clear this conception has multi aspects and it is needed in more physico-chemical and mathematical details. For example the concept of “superadiabaticity” that used for characterizing the regimes with anomalous high temperature in filtration combustion waves has principally different matter in the cases of stabilized and travelling waves. In general one may define the EE conception as some additional energy that accumulates ahead of the flame front during the combustion process from internal or external sources.

On the other hand, the flames with energy excess demonstrate the properties typical of only this type of flames. They are anomalous high combustion rates, anomalous wide regions of existence, exotic structures of fronts, etc. The EEF theory is not sufficiently advanced and fails to answer many questions concerning structure, stability, the maximum extension of flammability limits and the blow-off characteristics. Such EEF as cellular and spin flames with intrinsic three-dimensional structures of combustion zones are strongly nonlinear phenomena and require the adequate methods of analysis. In other words, EEF properties, peculiarities and other characteristics must be the subject of special investigations.

Based on the above examples one may draw conclusion on the wide range of possible applications of energy excess flames. The unusual properties and characteristics of EEF are rather attractive for use in combustors operating as sources of heat, incinerate burners of dangerous and toxic substances, and chemical reactors [33]. There are great possibilities, in particular, owing to the absence of link between the composition of combustible mixture and flame temperature, which is quite common for usual flames. This property of EEF is particularly important for the problem of fire and explosion safety because the flame temperatures and flammability limits play here significant role. The variety of the mechanisms of EE implementation determines great variety of applications based on EE principles. The given examples of combustor systems confirm this viewpoint.

Thus, the flames with excess energy are widely spread in nature but they are insufficiently explored. Further accumulation and analysis of data on excess energy flames will promote their classification and evolution of conventional concepts on this interesting phenomenon. Further purposeful investigation of properties and characteristics including rate characteristics, flammability limits and mechanisms of flame propagation will promote not only evolution of the theory of these flames but also the progress of effective nontraditional converters of chemical energy, reactors and technologies for various purposes.

Acknowledgements

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